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A NEW METHOD FOR AUTOMATIC TRUCK DISPATCHING IN AN OPEN PIT MINE

by

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ABSTRACT

We propose an advanced truck dispatching system which uses mathematical optimization approaches including integer programming, nonlinear networks and the assignment problem. The system produces better operation control than existing algorithms. Furthermore, it provides planning tools for choosing equipment and finding an equilibrium between the quality and quantity of production.

Key-words : open pit, mines, truck dispatching.

RÉSUMÉ

Nous proposons un système avant-gardiste d'assignation en temps réel des camions dans une mine à ciel ouvert utilisant des techniques d'optimisation mathématiques : programmation en nombre entier, réseaux à coûts non linéaires, problèmes d'affectation, etc. Ce système assure une utilisation de l'équipement disponible meilleure que celles obtenues avec les algorithmes existants. De plus, il fournit des outils de planification pour le choix et la localisation des équipements et pour trouver un équilibre économique entre les objectifs de quantité et de qualité de la production.

Mots-clés : mine à ciel ouvert, affectation, camions, temps réel.

INTRODUCTION

Truck dispatching in open pit mines has become increasingly integrated over the last 15-20 years. Three generations of truck dispatching systems can be identified.

Before the advent of truck dispatching in the true sense of the word, the practice was to assign trucks to shovels and shifts according to a production plan. Each truck remained with its assigned circuit throughout the shift unless a shovel broke down. In Fig. 1, which shows gains in productivity as a function of the increasing sophistication of dispatching systems, this system is called "fixed circuits". The three generations of dispatching are seen in relation to it.

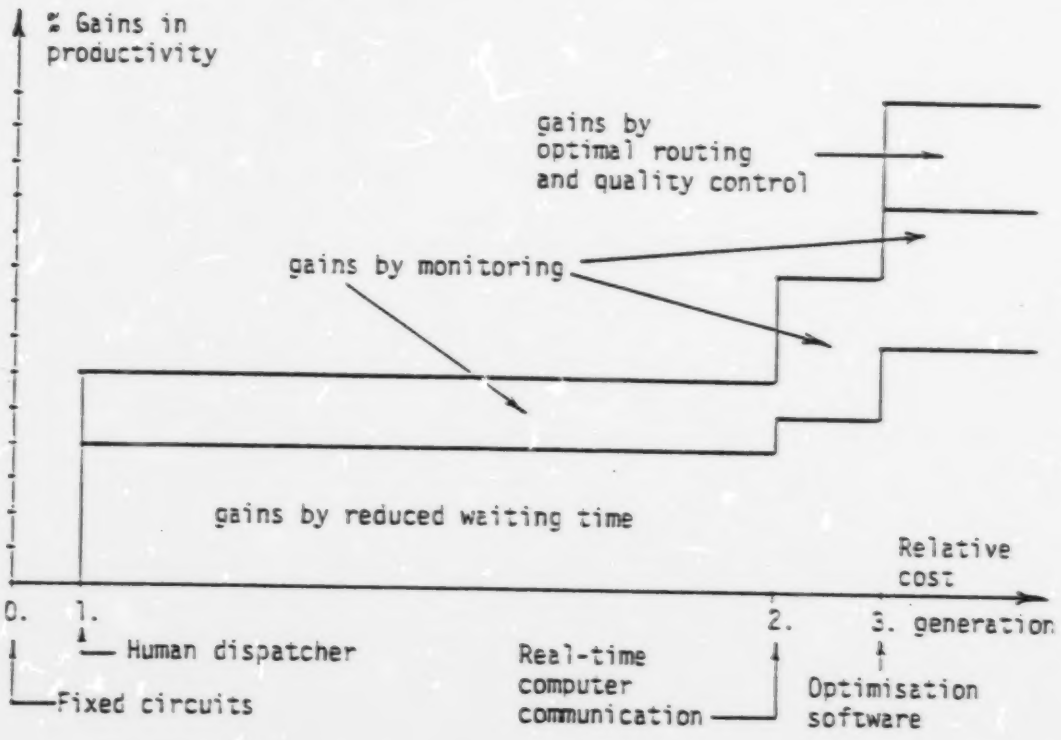

Figure 1. Gains in productivity according to the tree generations of dispatching.

Truck dispatching began modestly with a dispatcher who from a strategically located cabin kept track of the situation in the pit. He could reduce truck waiting times at the shovels by shifting empty trucks' destinations. The destinations could be transmitted to the trucks by numbers on a light board. It is, however, difficult in larger systems to pursue the two objectives of dispatching – waiting time reduction and maintenance of the production plan – without computational aids. This led to the dispatching table (Mueller, 1977), which is an analogue model of the circuits, where markers substitute for the trucks. From this point the stage was set for introduction of the P.C. (Young, 1984).The analogue model is programmed and the computer calculates truck destinations as suggestions to the dispatcher who remains in full control and transmits destinations to the trucks. Radio communication with shovels and trucks could be introduced here. This constitutes the first generation of truck dispatching systems and is characterized by the waiting time reducing procedure, which is used either directly by the dispatcher or organized in the P.C. The gains, which are shown on Fig. 1 at "human dispatching" are due to reduced waiting times, and because the monitoring of operations also increases the performances of truck drivers.

The second generation of dispatching systems preceded some of the first generation developments. They emerged before the P.C. This type of system is mainly characterized by automatic data transmission. Trucks' locations are detected by sensors and sent to the computer, which calculates destinations using a procedure which is basically the same as the procedure used by the dispatcher of the first generation system. The assignments are sent to the trucks directly and appear on a screen in the truck cabin. The force of such a system is that the dispatcher no longer needs to communicate the destinations to the trucks nor to keep track of

the trucks. In Figure 1, this system is called "real time computer communication". There are some gains by further reduced waiting times and more gains due to better monitoring made possible by continuous sensing. Reporting becomes automatic (Crosson, 1977; Charlemagne, 1979).

In third generation truck dispatching systems, dispatching is carried out by an optimizing algorithm, which is more or less closely related to the establishment of the daily production plan. The hardware could be the same as in second generation dispatching. At this level the computer is becoming the instrument which makes the mining operation truly integrated. All loading and transportation is carried out according to an optimal daily plan and continuously adjusted to changes in the state of the production system. It also becomes increasingly possible to orient mining towards certain grade expectations. This third generation of dispatching systems is called "optimization software" in Fig. 1. The gains in productivity are increased in term of waiting time reduction because of the optimization procedure, and there are additional gains due to route optimization and the quality of blending (White, 1981; White, 1983; Clevenger, 1983; McInnis, 1985). This paper presents a new third generation truck dispatching system with an even better integration of planning decisions and a more powerful optimization algorithms.

GENERAL DESCRIPTION OF THE SYSTEM

Figure 2 schematically illustrates the system and its interaction with the mine environment. The computer system handles all three steps in the production planning process : the choice of equipment, the calculation of the operational plan, and automatic truck dispatching.

The planner is reponsible for the first two steps. He first chooses which pieces of equipment should be operated to satisfy production and quality objectives. This is done interactively with the computer using the

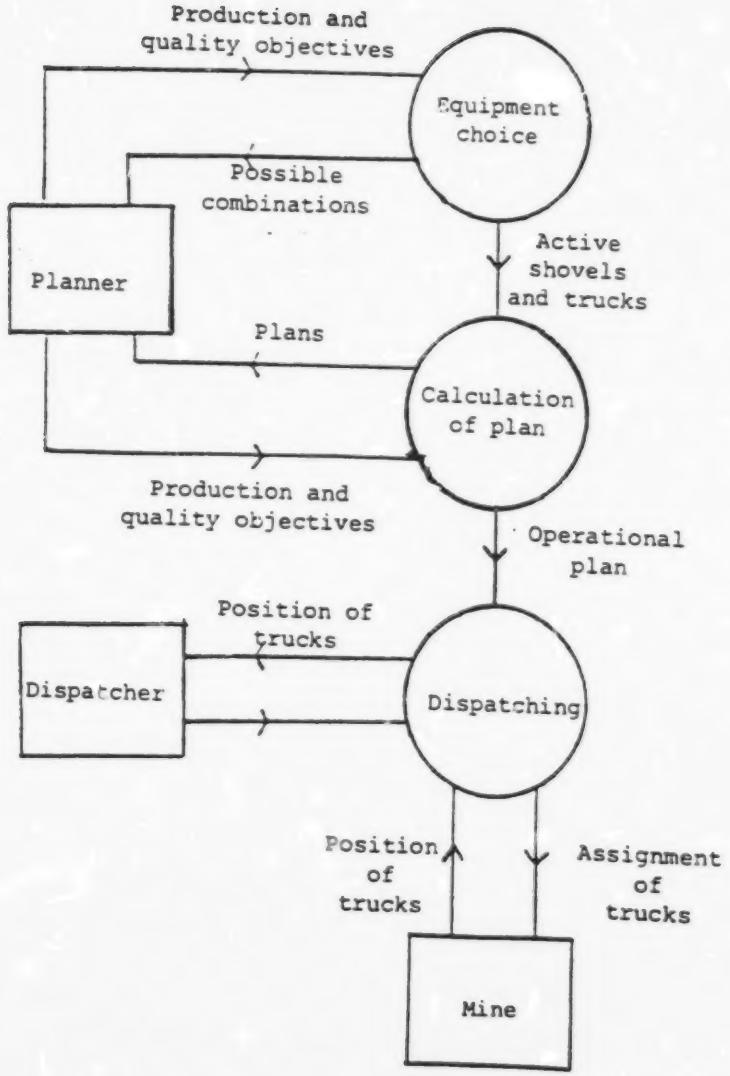

Figure 2. Diagram of the system.

"equipment choice" module. When the equipment has been chosen, the system enters the "operational planning calculation" module in which production estimates are calculated. The planner may then modify the objectives, revise equipment choice and recalculate production, or he may accept the plan provided. The accepted plan is transferred to the "dispatching" module where it serves as a criterion for truck assignment.

The dispatching module is directly linked to production. It interacts first with the mine, by tracking the position of trucks and transmitting truck assignments via a telecommunications channel. It also interacts with the dispatcher who can observe the movement of trucks on a screen and can enter information on equipment breakdowns to the computer.

Choice of equipment

There is usually little flexibility to determine the number of trucks and shovels : operators must be informed in advance of their work schedules. Therefore, the number of trucks and shovels used are treated as entry to satisfy requirements. A few operators may be added at the last minute if there is any equipment available. The set of operational shovels and their locations in the mine are known. Each shovel has access to several benches of material with different properties (from one to four benches). Note that it is not easy to move a shovel over a large distance as these are electric shovels powered through cables. So the problem consists of determining the active shovels and the benches to which they should be assigned in order to satisfy the quantity and quality objectives as far as possible.

This is a difficult problem given the large number of possible combinations of shovels and benches. And, in addition to quantity and quality considerations, a whole series of other factors must be taken into account : preferences for current modes of operation, the work required to transfer a shovel to a different bench, the order in which benches can

most easily be extracted, the need to finish one bench in order to obtain access to a zone located behind it, etc.

To make a good choice, we propose an approach which combines the operator's judgment with the calculating power of the computer. The central element of the system is a linear programming model allowing the computer to evaluate the maximum production while respecting quality constraints for a given location of active shovels. With this model, over 2000 combinations of shovel locations can be evaluated per minute on a PDP-11.

To reduce the number of calculations to be evaluated, the operator first fixes the main parameters which describe the kind of solution desired. He determines the number of shovels operating in the ore, the number operating in waste material, and the number in each mine. Similarly, he limits the choice of benches for each shovel according to priorities and preferences. The operator then asks the computer how many combinations of shovel locations are possible under these conditions and obtains an estimate of the calculation time required to evaluate them all. If the computer time required is considered reasonable, the operator requests an evaluation and obtains the best combinations in decreasing order of production. If the estimated computation time is too large, the operator can specify his preferences more precisely in order to limit the number of possibilities. If the best combinations evaluated are not satisfactory from a production standpoint, the operator can modify his preferences and explore other possibilities.

The planning step is carried out at the beginning of a shift if there is a change in the objectives, the number of shovel operators or the number of truck drivers. It can also be carried out during the shift as needed if a breakdown or other incident changes the operating conditions.

Operational plan

The second step of the planning process consists of determining the operational plan for the equipment selected. The number of trucks, the number of shovels and their location are fixed. The plan determines the activity level of each shovel and the routes travelled by the trucks to best meet objectives concerning the quantity and quality of ore transported. At this step, we propose a more realistic model of the ore transportation problem than that provided by the linear programming models of the planning stage. Linear models do not consider the increased waiting time which occurs when the capacity limits of shovels or the crusher are approached. In addition, they handle the quality requirements by setting upper and lower limits on the grade of the ore and other characteristics of the mixture. Such models produce extreme solutions : some shovels will work at their maximum capacity, while others will be very little used. In some cases, two shovels in the same type of ore may have quite different activity levels. In addition, solutions are generally at the limits of acceptable quality intervals. These solutions are acceptable as a first approximation to be used in determining the location of the shovels, but they cannot be used for generating an operational plan in real time.

To obtain a more realistic plan, we propose a non-linear programming model which takes into account the increase in waiting time with the congestion of shovels and the crusher, and which produces a better equilibrium between quantity and quality objectives. The extraction plan is determined by solving a network problem with nonlinear costs. The variables are the number of trucks loaded at each shovel and travelling on each route during the period considered. The only explicit constraints are the flow conservation equations; the number of trucks arriving at a point must be equal to the number leaving it. All other factors are considered in the objective function to be minimized.

A first group of objective function terms ensure that production is maximized by measuring the square of the difference between the capacity of each shovel and the number of trucks loaded. A second group of terms represents the quality objectives. For example to achieve the desired average grade, a penalty function is used as shown in Fig. 3.

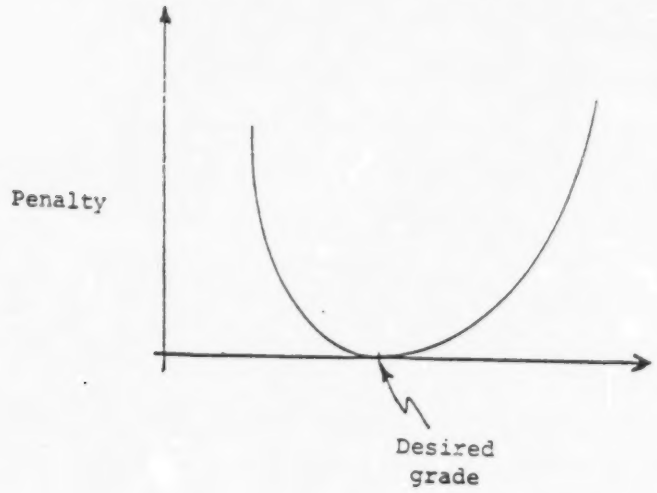

Figure 3. Penalty associated with deviations from desired grade.

The parameters for optimal concentration by Humphrey's spiral have been set for the average grade. Any deviation from it will result in loss of the heavy iron ore grains to the tailings. In the left branch there is a surplus of light grains which will flush some iron ore grains with them and in the right branch there is a surplus of heavy grains, of which some will be pushed to the tailings (Dallaire, 1978).

Similarly, other quality objectives are also expressed as penalty functions measuring the cost of diverging from target values. Thus, the model seeks an economic equilibrium between tonnage and quality.Tonnage is reduced to increase quality only if this is profitable.

The last term in the objective function ensures that the number of trucks used is equal to the number available. This term is equal to K times the square of the difference between truck availability time and

truck operating time. The parameter K is adjusted during the solution process to obtain the desired precision of the number of trucks. The truck availability time is equal to the number of trucks multiplied by the duration of the planning period. The truck operating time includes total loading and unloading times, and total travel times estimated using average times multiplied by frequencies. It also includes the waiting times at each point as a nonlinear increasing function of the number of trucks served. This function is derived from queuing theory. This last term in the model allows resulting waiting times to be taken into account during operational planning. The importance of this will appear clearly at the dispatching level.

This network problem with non-linear costs is quite easily solved. For a mine with 15 shovels and 5 unloading points the network includes 40 nodes and less than 100 arcs. A network of this sizes requires less than 1000 words of memory and can be handled by a small computer. We have developed a specialized version of the reduced gradient method to solve this problem. Our algorithm adjusts the various parameters during the solution process to achieve a solution with the desired accuracy. A solution giving the optimal number of trips on each route to three significant figures in obtained in ten sconds on a PDP-11.

This nonlinear cost model has the advantage of producing operational plans which are much more stable than linear models in the face of parameter modifications. Fig. 4 shows the number of trips per shovel for eight production plans computed for the same shovel numbers and positions, and for increasing numbers of trucks. The differences between shovels are smaller and curves more regular than those produced by a linear model. This stability simplifies the task of the operator who adjusts the operating parameters to obtain a plan which meets production objectives.

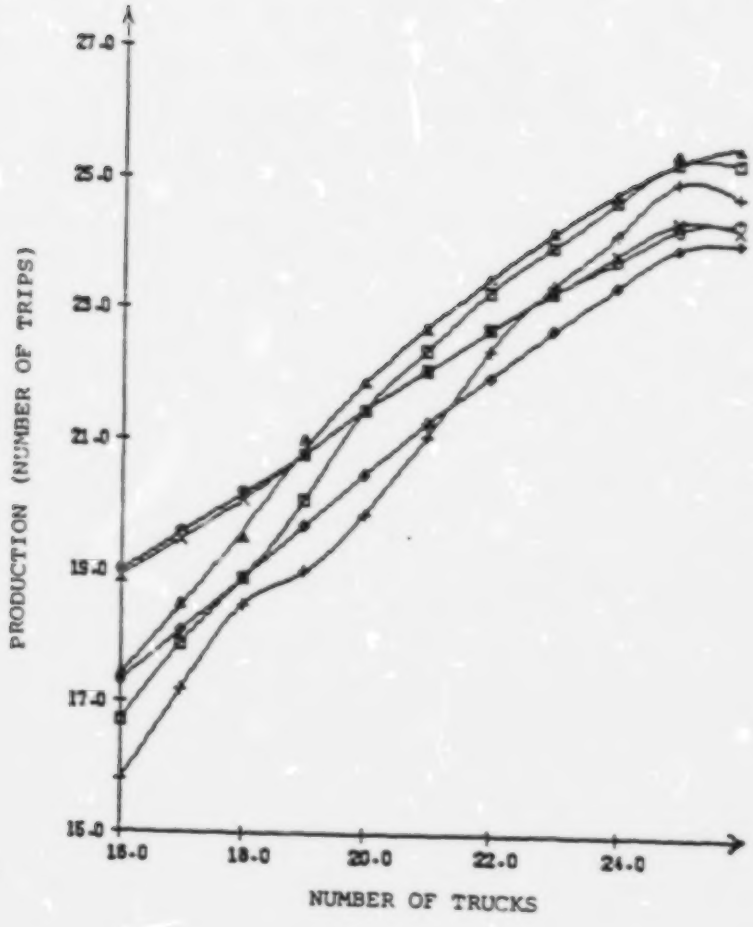

Figure 4. Number of trips per shovel as a function of the number of trucks.

Automatic truck dispatching

The last step in the decision process determines the real time assignment of trucks. After each unloading, the system communicates to the truck its next loading point. After loading, the truck proceeds to the unloading point which has been previously fixed for each shovel. These assignment decisions are taken so as to implement the operating plan as far as possible and thus to obtain the best performance in terms of the quantity and and quality objectives.

The dispatching system first serves a communication function. This function includes the determination of the position of the trucks, the evaluation of travel and loading times and the estimation of the times at which each truck and each shovel will become available; the system also ensures the communication of truck assignments. Fig. 5 illustrates the equipment used.

Radio transmitters (1) are placed at strategic locations in the mine (road intersections, shovels, dump entrances, etc.). Each transmitter emits a unique signal which is recorded in the black box of a truck (2) as it passes the transmitter. The transmitter (3) enables the truck to inform the computer (4) every six seconds of the contents of the black box. This

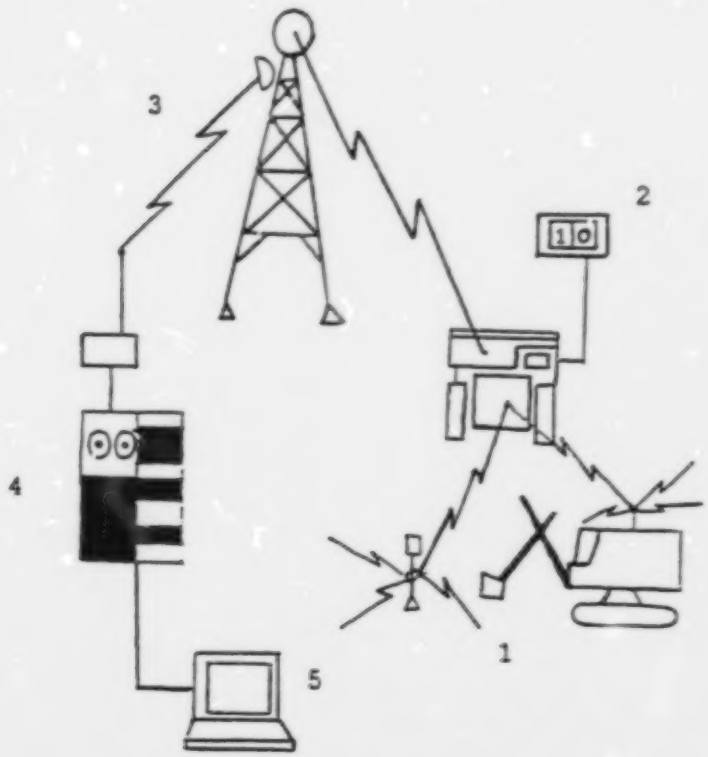

Figure 5. The communication system.

information is processed treated by the computer to establish the position o. trucks and to post all necessary information on the dispatcher's terminal (5). As the computer knows the location of all the trucks, it also knows when they will require a new assignment. The computer (4) determines the assignment and transmits it to the truck via the communication radio (3), posting the code associated with the truck's new destination on the numerical screen (2).

The decision method developed for this step considers both the truck to be assigned and the trucks which will next become available. It thus optimally assigns around fifteen trucks to the next shovels to become available. This is a major improvement over the Charlemagne system then used at Mont-Wright, and several other systems which consider only the first truck. These short-term oriented approaches may produce decisions which are quite far from the optimum. Fig. 6 illustrates the assignment problem handled by our system.

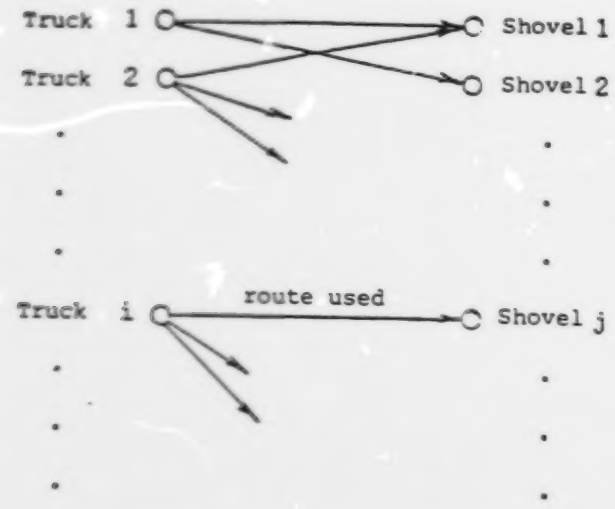

Figure 6. Truck assignment.

The arc between truck i and shovel j exists if the route from the unloading point of truck i to shovel j is used in the operational plan. The arcs therefore represent all possible assignments of each truck and all possible sources of a truck for each shovel according to the plan. The problem is thus to choose one and only one arc for each truck and at most one arc arriving at each shovel.

The costs to be minimized in this assignment are the deviations with respect to the plan. Several measures can be defined. White and Olson (1983) propose a cost based on the difference between the estimated time of arrival of trucks at the shovel and the expected time according to the plan. The expected time is given by the frequencies established in the plan assuming that trucks are equally spaced. This method does not take advantage of more rapid loadings to send more trucks. In addition, it keeps on sending trucks at the same frequency even if loading time is longer than expected and trucks are kept waiting. Such a measure will generate operating problems for very busy shovels which have highly variable loading times. We therefore propose a different measure which avoids this problem. Fig. 7 shows the general idea behind this measure.

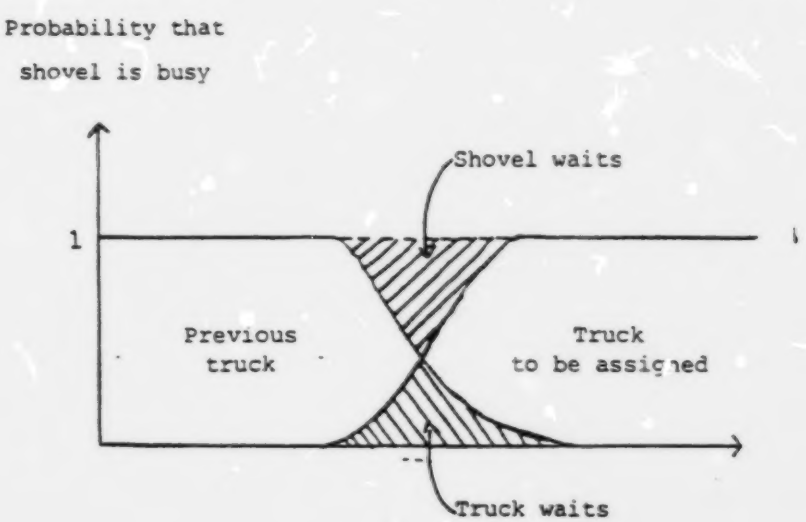

Figure 7. Evaluation of probabilities of waiting time for an assignment.

The proposed measure is evaluated as follows : the probabilities that the truck to be assigned and the last truck previously assigned will be present at the shovel are calculated. The expected waiting times for the truck and the shovel are then calculated for the assignment being considered. Our measure is then the difference between these waits and those established in the plan. With this measure, assignments tend to reproduce the same shaded areas between trucks independently of loading times. Thus when loading times increase, trucks arrivals are less frequent, and they are more frequent when loading times decrease. On average, trucks arrive with the frequency indicated in the plan, but in addition their spacing is synchronized with fluctuations in the speed of the shovels.

The assignment problem for around fifteen trucks is solved optimally in less than a quarter of a second on the PDP-11. This problem is solved each time a truck becomes available for assignment. The assignment problem is solved using the following procedure by a shifting horizon method.

Truck assignment procedure

1. Questioning of the trucks and estimation of the times at which each truck and each shovel will become available;
2. Solution of the assignment problem for around fifteen trucks;
3. Communicate assignments to the available truck(s), cancel the assignments of trucks which are still occupied, and return to 1.

Tests

We will see in what follows that the production estimated by the planning model can be achieved in practice using our dispatching model. First, we measured the potential improvements in production at the Mont-Wright mine due to the use of our models as compared with Charlemagne

system. This test was carried out by comparing actual production with the production forecast by our planning model.

Using statistics concerning mine operations, we chose a period of 2½ hours within which there were no fluctuations in the number of shovels and trucks, and where the grade of the ore at each shovel was constant. Using data on loading, unloading and travel times, an operational plan was calculated and the results were compared with observed production and waiting times at Mont-Wright under the same conditions. During this period, 6 shovels and 15 trucks were used and the grade objective was 31.0% (±0.5%). The results are presented in Table 1.

Table 1. Operational plan vs Mont-Wright.

	PRODUCTION (# trips)			TRUCK WAITING TIME (min)	SHOVEL WAITING TIME (min)	GRADE OF BLEND
	ORE	WASTE	TOTAL			
PLAN	65.4	64.7	130.1	73.3	274.1	.3107
MONT-WRIGHT	65.0	51.0	116.0	267.5	338.7	.317

The operational plan gives 14 more trips than the production actually achieved at Mont-Wright over the same period. This is a difference of 11%. In addition, the grade of the mixture produced at Mont-Wright was 31.7% Fe, while the operational plan produced much better quality with 31.1% Fe. It is clear that the increase in productivity is due to the reduction in truck waiting time. In fact, truck waiting time is reduced by 72.5% in the calculated operational plan as compared with actual operations.

It is difficult to compare a truck dispatching model with the production obtained using current system. It is impossible to run the two

systems in parallel to compare their performance because one single system must communicate assignments to trucks. Similarly, we cannot operate the two systems one after the other in the same conditions; once the ore has been transported, it is no longer there to evaluate the second system, and the same loading and transportation times cannot be reproduced.

To obtain a situation in which the two dispatching systems could be compared, we developed a simulation of the mine. The simulator randomly generates the travel times and loading and unloading times for trucks and updates the data bank of the system. It replaces the questioning of trucks which provides information on the times at which the trucks pass the transmitters in the mine. The simulator generates activity times according to Erlang distributions with means and standard deviations corresponding to observed values. Fig. 8 shows the exchange of information between the dispatching algorithm and the simulator via the data bank.

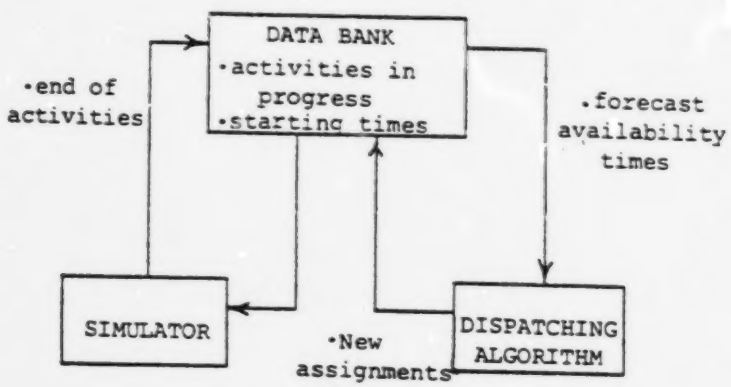

Figure 8. Truck dispatching in a simulated mine.

A comparison was carried out between the the Charlemagne system and the new dispatching system using the simulator to reproduce 15 hours of typical operations. This duration is divided into 12 periods with different numbers of shovels and trucks, and different activity times. An operating plan was calculated for each period and the simulator was used with the appropriate distributions. The results are presented in Table 2.

Table 2. Results obtained from the different systems.

PERIOD	PRODUCTION BY CATEGORY (#TRIPS.)									WAITING TIME (MIN.)					
	PLAN			CONTROL			CHARLEMAGNE			PLAN		CONTROL		CHARLEMA	
	OR.	W.	OVE.	OR.	W.	OVE.	OR.	W.	OVE.	TR.	SH.	TR.	SH.	TR.	SH.
23H30-00H30	23.6	19.2	9.4	25	20	9	23	18	7	28	173	31	109	65	99
00H30-2H30	50.4	19.8	23.4	55	17	25	54	17	18	117	147	112	144	157	97
2H30-3H30	20.9	7.45	8.65	20	9	9	21	7	8	15	75	29	75	32	85
3H30-4H30	20.9	7.45	8.65	19	8	10	24	5	5	15	75	19	68	41	90
4H30-5H30	24.7	18.4	8.7	26	20	8	24	20	9	18	130	10	141	15	137
5H30-6H30	20.7	29.7	8.1	20	27	9	21	32	5	29	105	48	108	52	96
6H30-7H30	20.7	29.7	8.1	20	28	7	22	32	5	29	97	30	110	54	97
7H30-8H30	21.5	23.0	8.8	20	24	10	23	25	7	33	77	42	80	43	73
13H30-15H30	34.2	63.8	10.4	34	61	10	37	58	5	36	279	20	273	30	303
16H30-17H30	24.4	10.3	8.5	25	11	7	24	8	7	13	107	37	100	28	90
17H30-18H30	19.5	19.7	11.0	21	19	8	21	20	11	46	52	39	64	60	69
21H30-23H30	37.4	48.6	20.8	35	54	20	39	49	16	97	117	97	117	126	103
TOTAL	318.9	297.1	134.5	320	298	132	333	291	103	476	1434	514	1389	703	1339
	750.5			750			727								

OR. : ORE
W. : WASTE
OVE. : OVERBURDEN
TR. : TRUCK
SH. : SHOVEL

Note first that there is a very strong correspondence for each period between the number of trips estimated in the operational plan and those carried out by our dispatching system, both for ore and waste material. In total, this correspondence is even stronger. We may therefore conclude that :

1. The dispatching system follows the plan;
2. The plans are realistic.

Next, note the gain in production of 3.2% over the Charlemagne system. The period of 15 hours with 750 trips is long enough to ensure that the results are significant in spite of the variance in the durations of the simulated ativities. For the waiting times, note again the good correspondence between the results of the plan and those achieved by our dispatching system. Note also that waiting time is reduced by 35% over the Charlemagne system.

Ten scenarios prepared by Quebec Cartier Mining with quality objectives including up to three parameters were examined. We find that the dispatching system once more follows the plan closely in quantity and quality. We obtained a gain in production of 2.0% over the Charlemagne system. Note that the gain for dispatching without quality constraints for those scenarios was 3.2% over the Charlemagne system.

This demonstrates that little production is lost to meet quality objectives unless the types of ore available are incompatible with these objectives. Using the equipment choice module to ensure compatibility, it is thus possible to obtain good results for both quantity and quality.

Table 3 presents two of these scenarios. Scenario 1 has a grade requirement of 31.5% ±0.5%. Four shovels with grade of 27.0%, 29.0%, 34.0%, 40.0% and a mean of 32.5% were available. Scenario 2 has the same grade requirement and a requirement of magnetite less than 0.40%. Four shovels were available with grades of 27.0%, 30.0%, 32.0%, 40.0% (mean of 32.3%) and magnetite 1.0%, 0.4%, 0.1%, 0.7% (mean of 0.55%).

Table 3. Scenarios with quality contraints.

	Production (# trucks)			Quality	
	ORE	WASTE	TOTAL	% IRON	% MAGNETITE
SCENARIO 1					
Charlemagne	85	34	119	31,9	—
Plan without quality control	85	42	127	32,3	—
Plan with quality control	84	43	127	31,7	—
Dispatching	82	46	128	31,9	—
SCENARIO 2					
Charlemagne	83	40	123	32,2	0,55
Plan without quality control	87	42	125	32,1	0,55
Plan with quality control	71	49	120	32,0	0,39
Dispatching	72	48	120	32,0	0,38

CONCLUSION

The proposed system gives excellent results in terms of the quantity and quality of ore extracted, and it achieves this with very short computation times through the use of very efficient optimization algorithms. In addition to the operational gains discussed in the text, this system also provides benefits at the planning stage through the use of the first two modules of the system. The equipment choice module and the operational plan establish conditions under which it is possible to achieve both quantity and quality objectives. In fact, rather than discovering at the end of the day that conditions were unfortunately unfavourable, and that objectives could not be met, these modules estimate the production in advance and allow conditions to be modified if it is not possible to satisfy the objectives. In addition, these modules allow objectives to be raised if tests show that it is possible to do better.

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